Global Decoupling on RHIC Ramp

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1. **Introduction**

2. **N-turn map and Three-ramp Corrections**

3. **Skew quadrupole modulation**

4. **Six coupling observables**

Why is the seminar here

1. Early planned seminars

Linear Coupling: Theory and Application

Theory: Linear coupling's action-angle parameterization
Matrix perturbation approach to linear weak coupling
Eigenmode behavior under linear coupling

Application: Measurement & Correction
Skew quadrupole modulation
six coupling observables and decoupling feedback

2. Rehearsal of PAC2005 invited talk (asked by Dejan and Fulvia)
Global Decoulping on the RHIC Ramp, 12 min.

Introduction

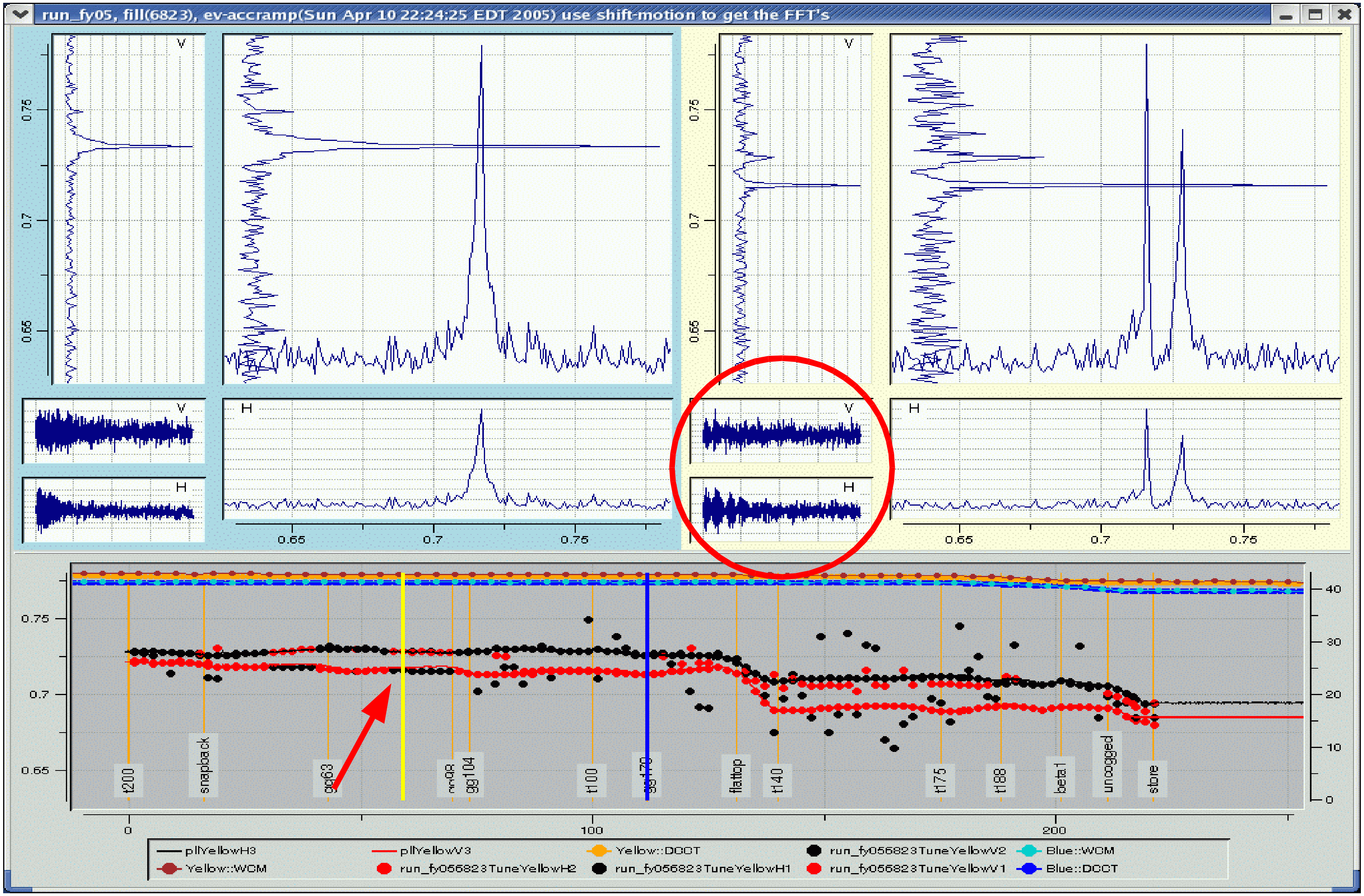
1. Linear Global Weak Difference Coupling(Resonance)

$$\begin{cases} x'' + k_x(s)x & = & -k_s(s)y \\ y'' + k_y(s)y & = & -k_s(s)x \end{cases}$$

Linear coupling caused by skew quadrupole and/or solenoid fields

- Linear and nonlinear
- Local and global decoupling
- Weak and strong
- Difference and sum

2. Coupling Indentifying on RHIC ramp



3. Global Decoupling Requirement for RHIC ramp

1) Tight working point space requires effective tune control.

However, coupling prevents the design tune settings,

coupling always enlarges the tune split.

2) Coupling also play roles in other issues,

like tune feedback, polarization, transition instability ...

3) For RHIC polarized proton run

design tune split 0.01 / flat tunes on the ramp

Goal: dQmin < 0.005

4. Why is decoupling on the ramp difficult

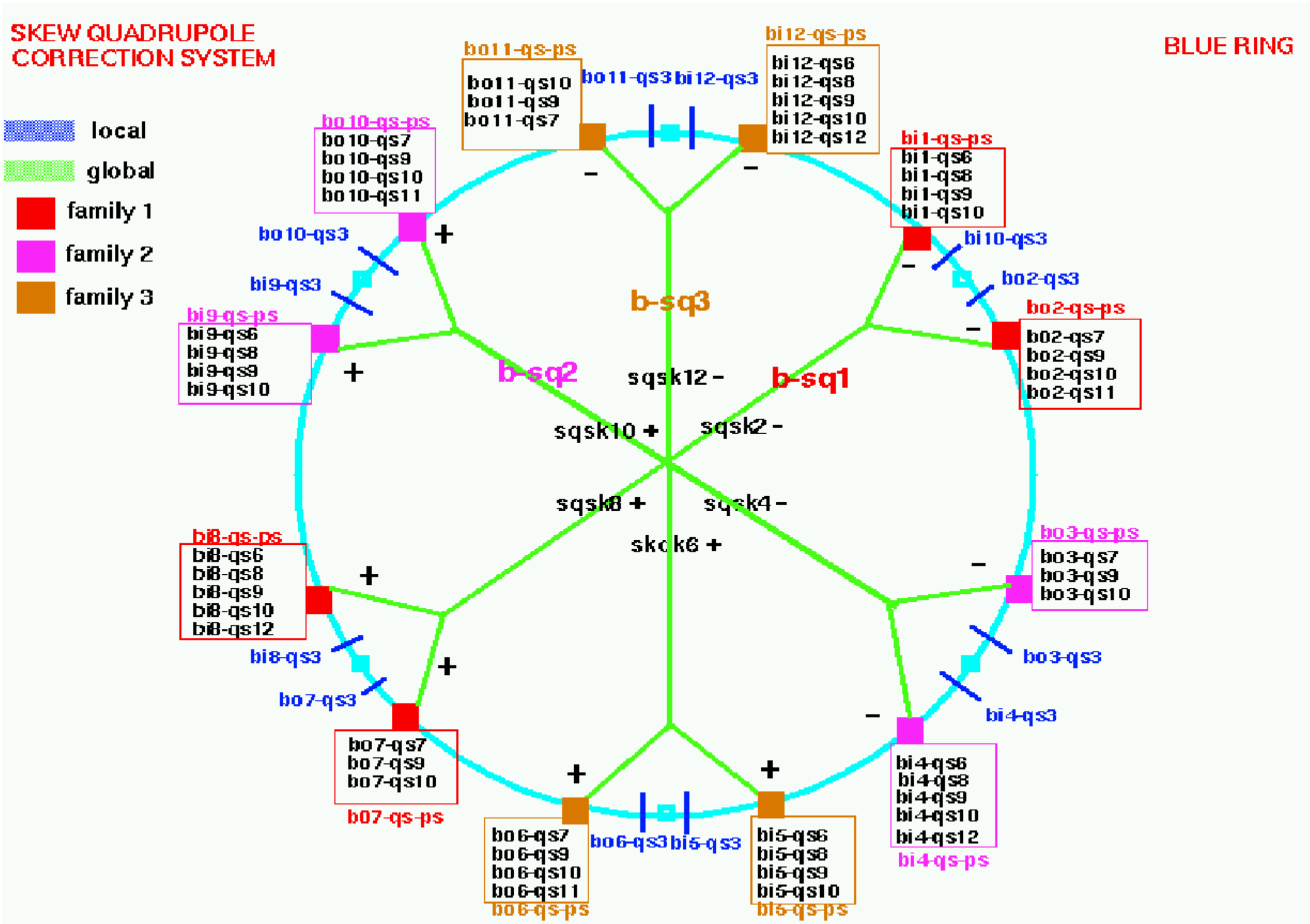
- Decupling on the ramp is different to that at injection and store. The conventional skew quadrupole scan is not suitble for ramp. Decoupling on ramp is more difficult.

1) Non-stop energy acceleration.

2) Design optics evolves on the ramp.
   such as snapback, beta squeezing, IR separation bumps.

3) Movements of the closed orbit on the ramp.
   vertical orbit in sextupoles produces coupling

5. RHIC correction skew quadrupole families



N-turn transfer maps

1. Principle

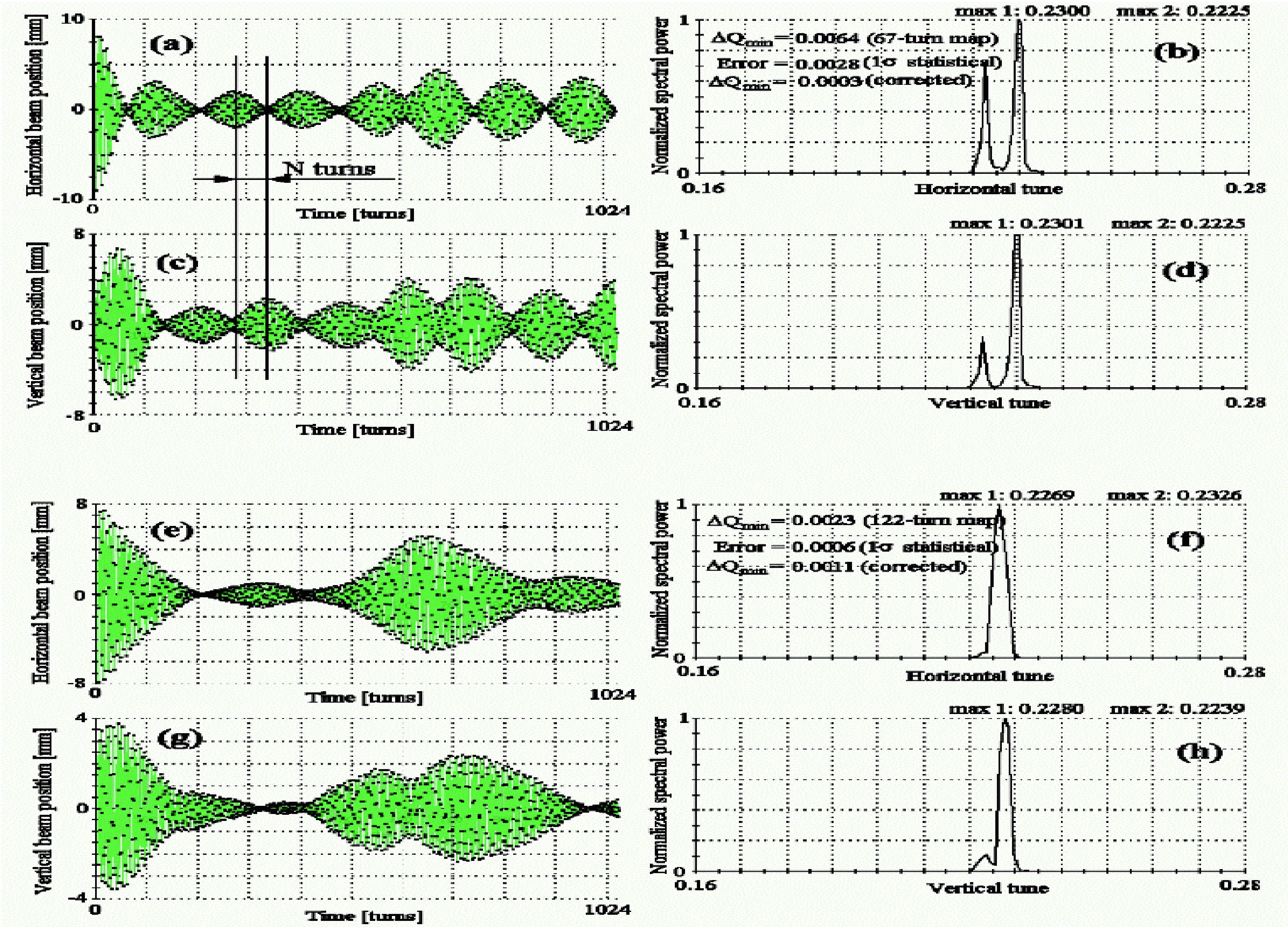
To get better S/N ratio, fitting the *N*-turn transfer matrix instead of one-turn matrix from the TBT BPM data.

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix} \qquad \mathbf{M}^N = \begin{pmatrix} \mathbf{A}_N & \mathbf{B}_N \\ \mathbf{C}_N & \mathbf{D}_N \end{pmatrix} \qquad N \sim \frac{\pi}{|Q_1 - Q_2|}$$

$$\mathbf{C} + \overline{\mathbf{B}} = (\mathbf{C}_N + \overline{\mathbf{B}}_N)\frac{\cos Q_1 - \cos Q_2}{\cos(NQ_1) - \cos(NQ_2)}.$$

Coupling correction strengths are calculated according to thin skew quadrupole and weak coupling approximation by Talman.

2. Verified at RHIC injection



3. Applied to RHIC ramp coupling correction

- This scheme depends on the valid BPM data.

  The TBT BPM data taken from tune meter kicking on the ramp. In the previous years, the quality of the TBT data prevented the reliable fitting of the N-turn map.

- This scheme strongly depends the optics model

  At high energy and low beta*, the used model is not accurate enough to give right skew quadrupole correction strengths.

- It hasn't been verified on ramp. Work is in progress.

Three-ramp Coupling Correction

1. The principle:

   three ramps to determine three unknowns

$$|\Delta Q| = \sqrt{\Delta^2 + |C^-|^2}. \qquad C^-_{tot} = C^-_{res} + C^-_{int}.$$

$$C^- \simeq \left(\sum_i \frac{1}{2\pi}\sqrt{\beta_{i,x}\beta_{i,y}}\right)\Big|_{\text{one family}} \times (k_s dl)$$

$$|C^-| \simeq 60 \times |k_{1s} dl|$$

2. It was occassionally used in RHIC run 2004.

   1) Three ramps are needed.
   2) It strongly depends on the optics model.

Skew Quadrupole Modulation

1. Skew quadrupole modulation

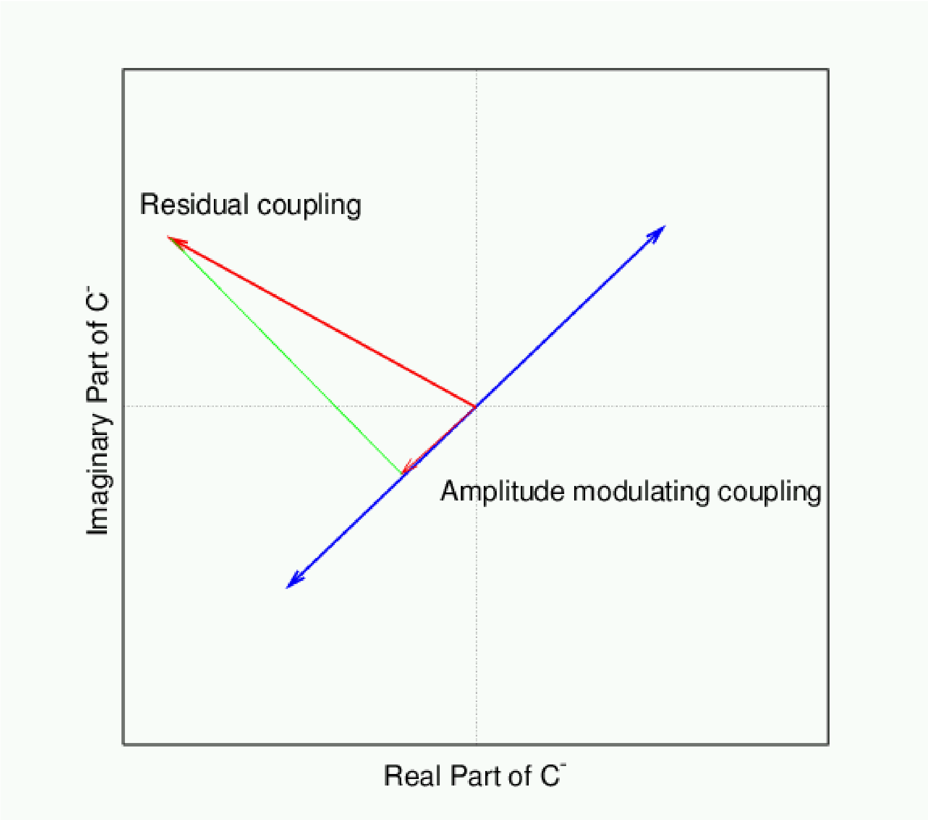
1) It was put forth for the ramp decoupling purpose.
2) It detects the residual coupling by modulating skew quadrupole strength to introduce an extract coupling into the machine.
3) The fast tune changes are tracked with a high resolution phase locked loop tune mesurement system.

2. Advantages of skew quadrupole modulation

1) no need to push the tunes to coupling resonance line
2) fast, modulation frequency on ramp is 0.2 Hz for RHIC.
3) less perturbation, modulation strength is small,
4) dynamic measurement, better S/N

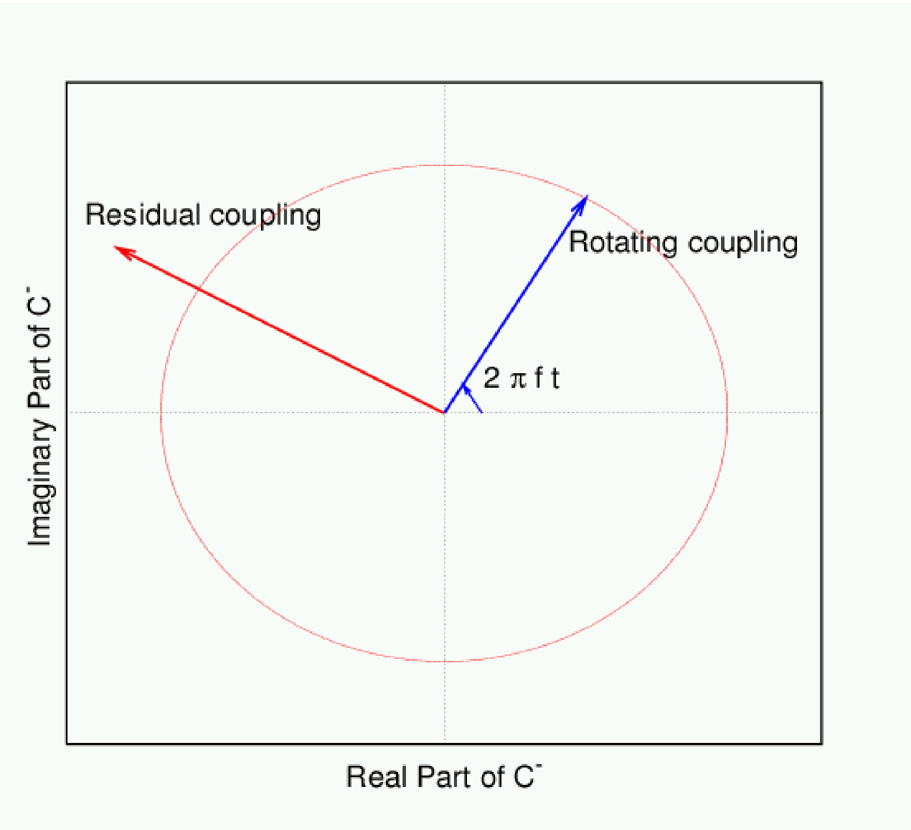
3. Two skew quadrupole modulations

Coupling amplitude modulation



$$C^{-}_{mod} = C^{-}_{mod,amp}\sin(2\pi f t)$$

Coupling angle modulation



$$C^{-}_{mod} = |C^{-}_{mod,amp}| \cdot e^{i2\pi f t}$$

Coupling Amplitude Modulation

1. Principle

amplitude modulated coupling: $C^-_{mod} = C^-_{mod,amp} \sin(2\pi f t)$

The eigentune split during the modulation:

$$\begin{aligned}(Q_1 - Q_2)^2 \quad = \quad & \Delta^2 + |C^-_{res}|^2 + \frac{1}{2}|C^-_{mod,amp}|^2 \\ & +2|C^-_{res}||C^-_{mod,amp}|\cos(\varphi)\sin(2\pi f t) \\ & -\frac{1}{2}|C^-_{mod,amp}|^2\cos(4\pi f t), \qquad (8)\end{aligned}$$

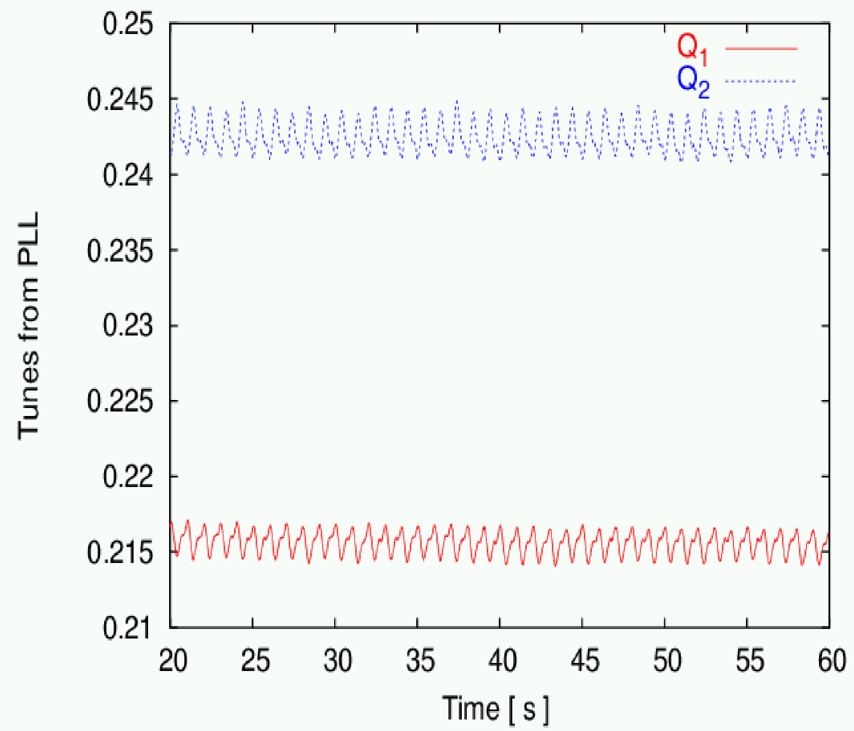
We define the projection ratio

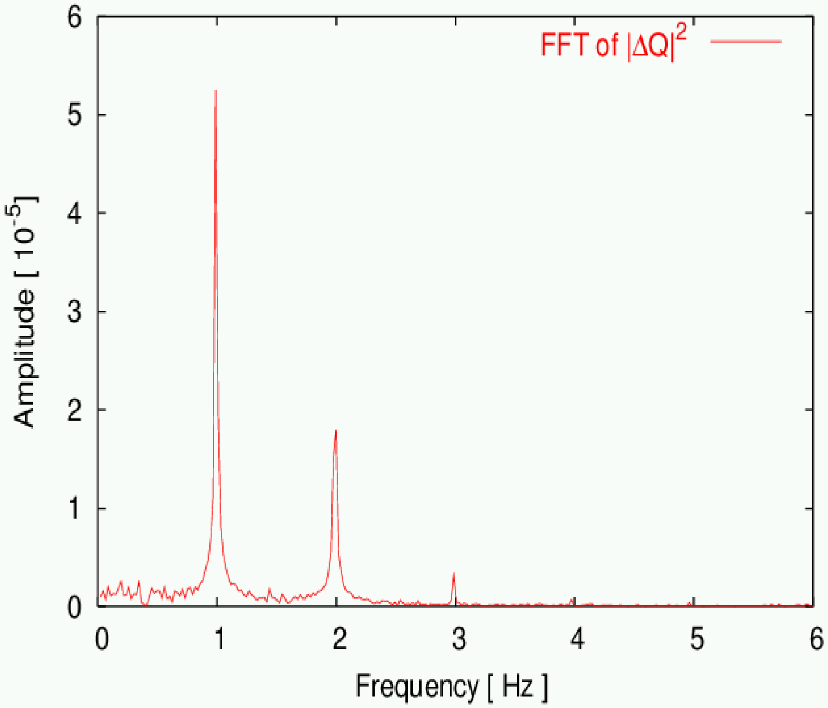
$$\kappa = \frac{|C^-_{res}|\cos(\varphi)}{|C^-_{mod,amp}|}.$$

from FFT of tune split square

$$|\kappa| = \frac{A_{1f}}{4A_{2f}}.$$

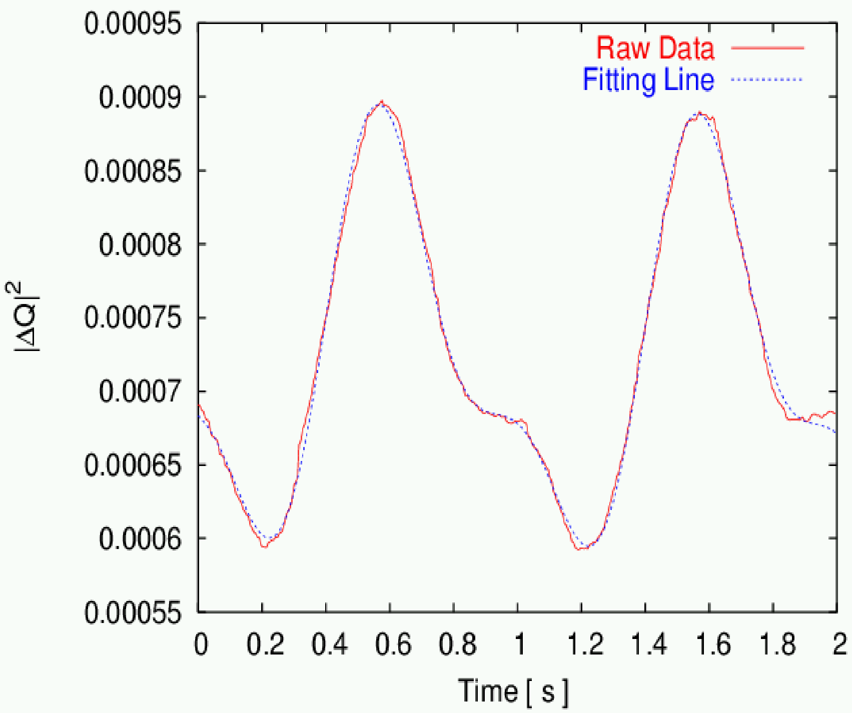
3. Verifying at injection and store

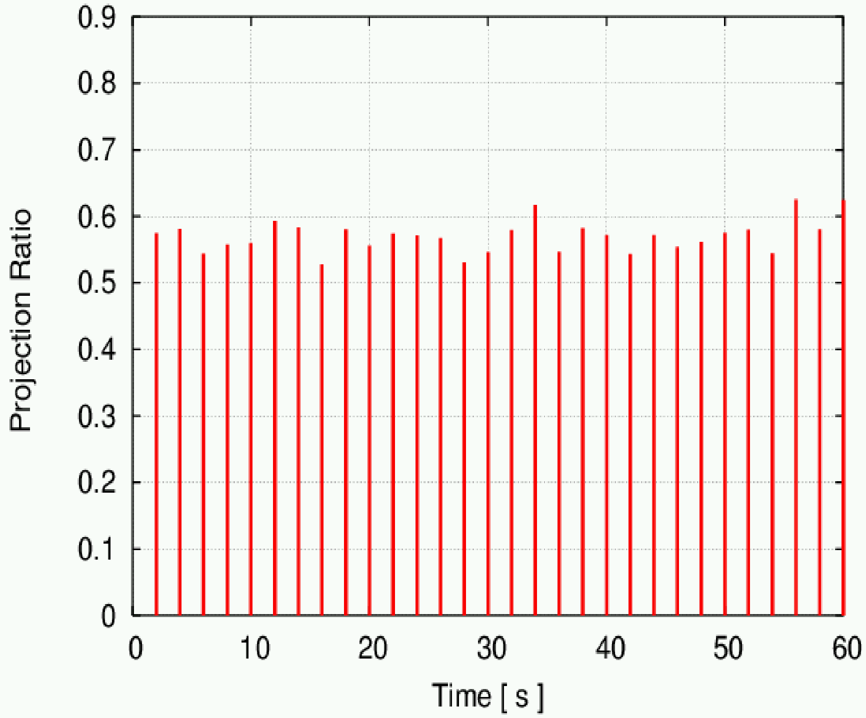




one coupling amplitude modulation at injection

4. Shorten the modulation to seconds



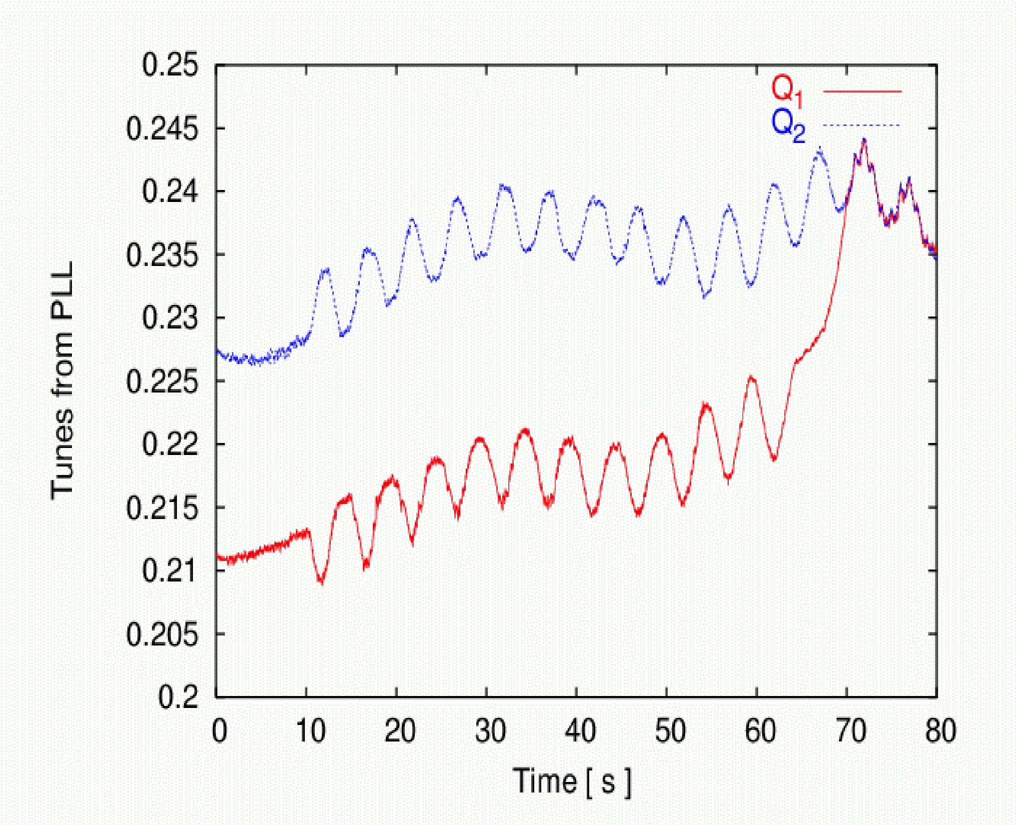


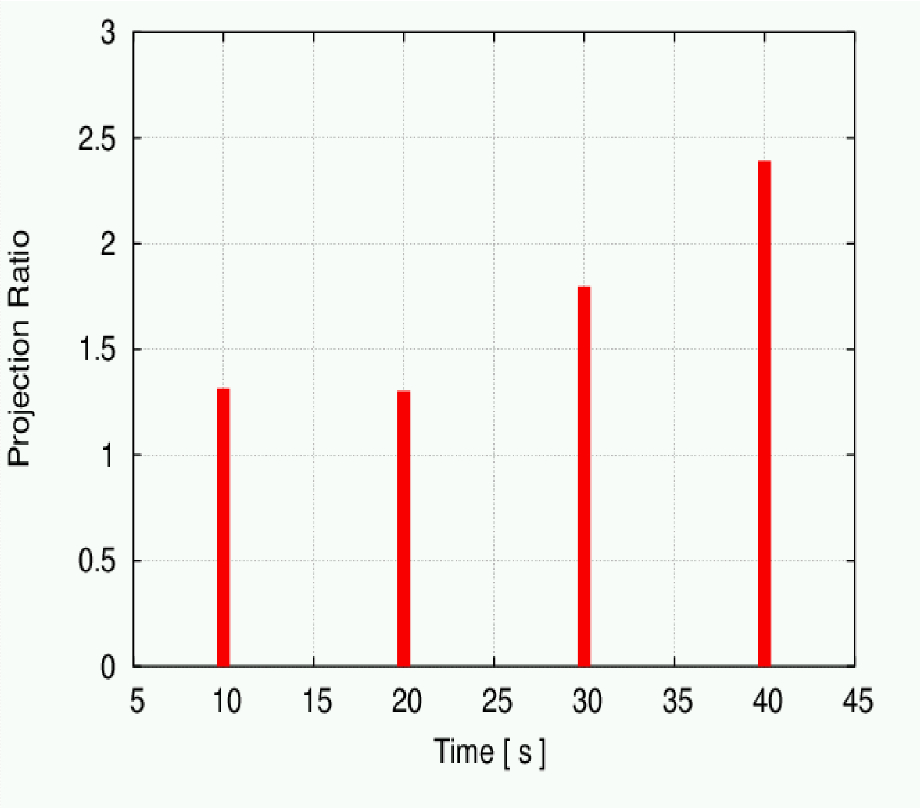
To shorten the modulation occupied time, linear regression is used.

$$
\begin{aligned}
f(t_i) &= A + B_1 \sin(2\pi f t_i) + B_2 \cos(2\pi f t_i) \\
&\quad + C_1 \sin(4\pi f t_i) + C_2 \cos(4\pi f t_i) \\
&\quad + E t_i + F t_i^2,
\end{aligned}
$$

$$
|\kappa| = \frac{\sqrt{B_1^2 + B_2^2}}{4\sqrt{C_1^2 + C_2^2}}.
$$

5. Test on the ramp





One example of coupling amplitude modulation on the ramp

6. Comments

- It is not fast enough.

Although one projection measurement was reduced below 10 seconds on ramp. However, to do correction needs at least two projections.

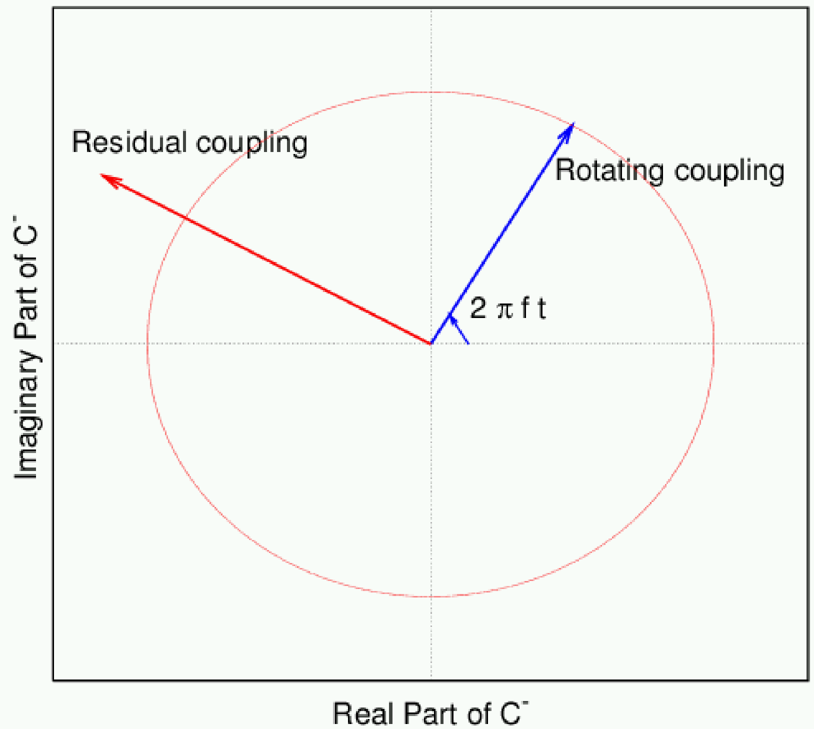
- It is not robust enough.

It is stongly depends on optics model. The modulation directions are calculated from the model. And FFT and linear regression were used, therefore the quality of the PLL tunes is a big concern.

- The correction and the measurement has loose connection.

Coupling Angle Modulation

1. Principle



$$|C^-_{res,amp}| = k\ |C^-_{mod,amp}|$$

During the modulation,

$$\Delta Q^2_{min} = \Delta^2 + (k-1)^2 \cdot |C^-_{mod,amp}|^2;$$

$$\Delta Q^2_{max} = \Delta^2 + (k+1)^2 \cdot |C^-_{mod,amp}|^2$$

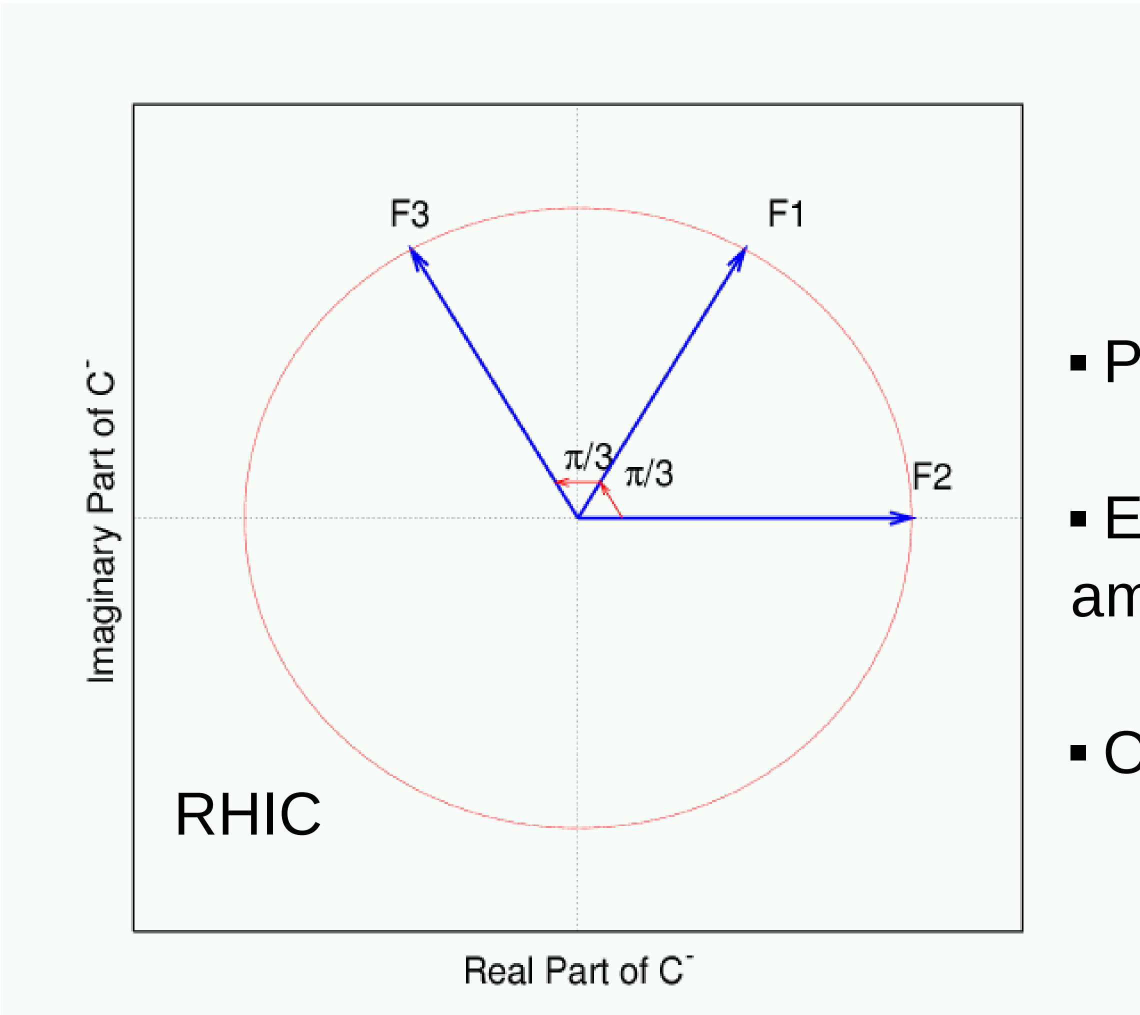
together with

$$\Delta Q^2_0 = \Delta^2 + k^2 \cdot |C^-_{mod,amp}|^2$$

k is given by

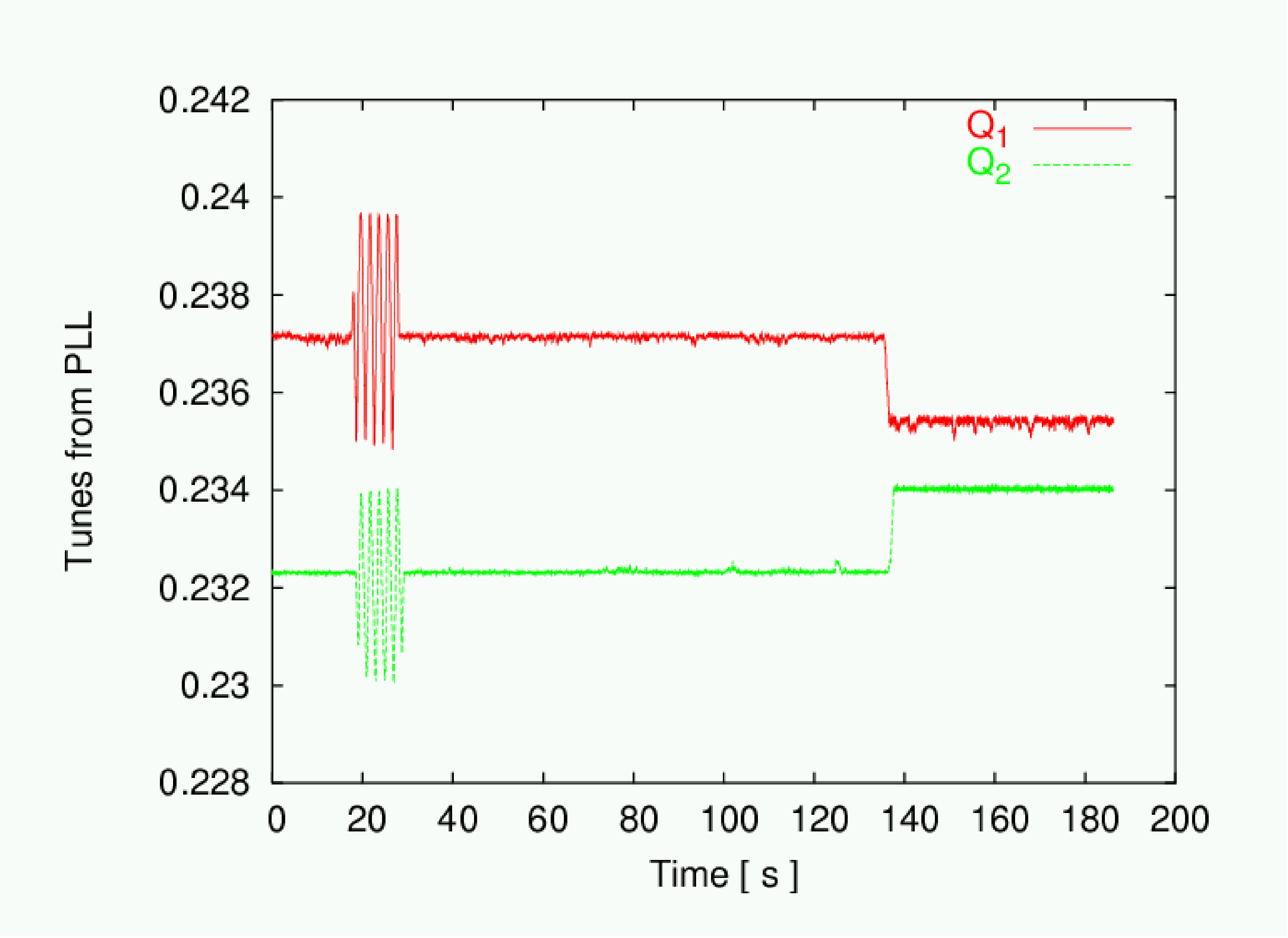
$$k = [4(\frac{\Delta Q^2_{max} - \Delta Q^2_0}{\Delta Q^2_{max} - \Delta Q^2_{min}} - \frac{1}{2})]^{-1}$$

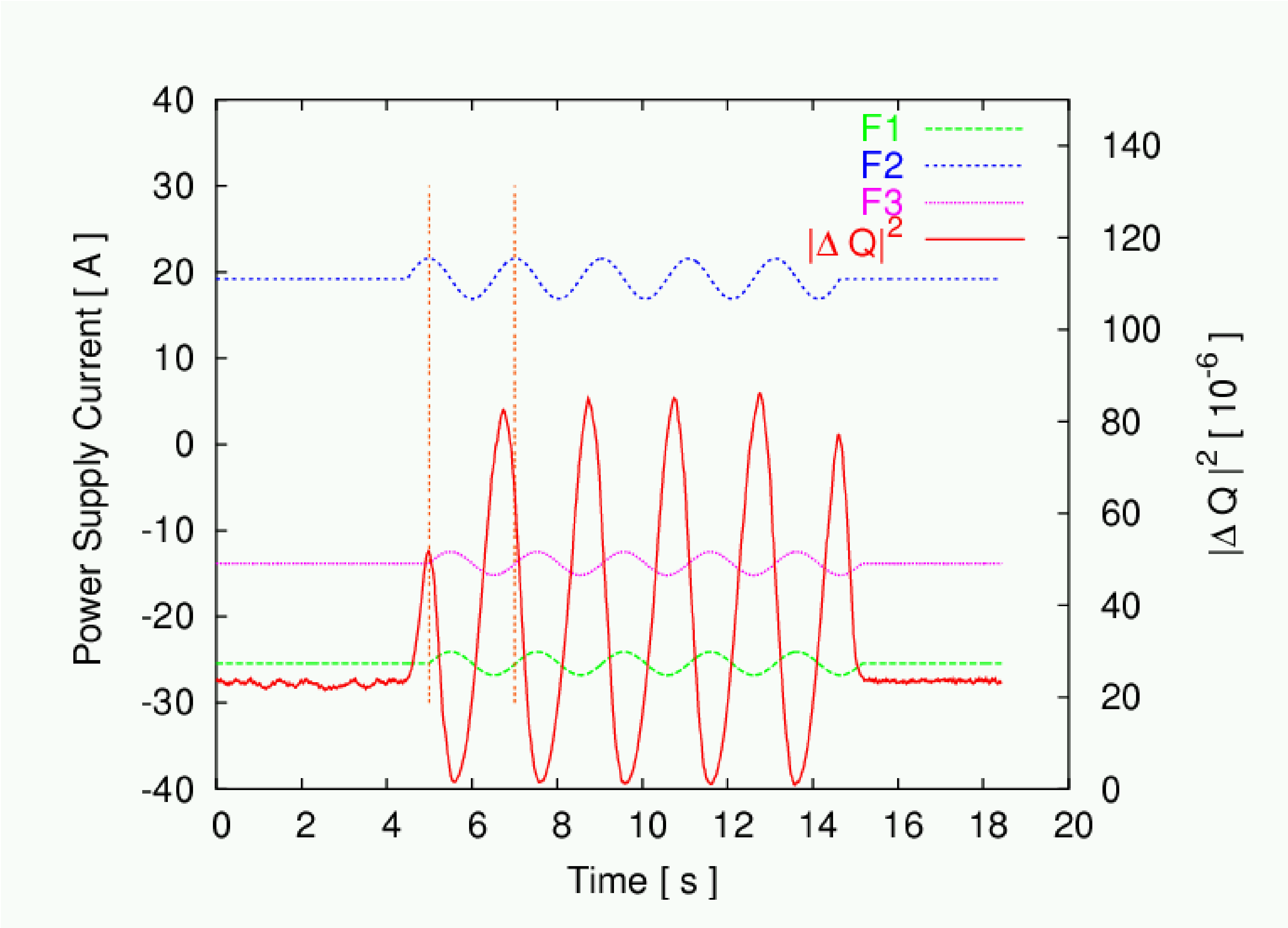
2. How to produce the rotating coupling



- Prepare orthogonal families
- Equal coupling modulation amplitude and frequency
- Out-of-phase modulations

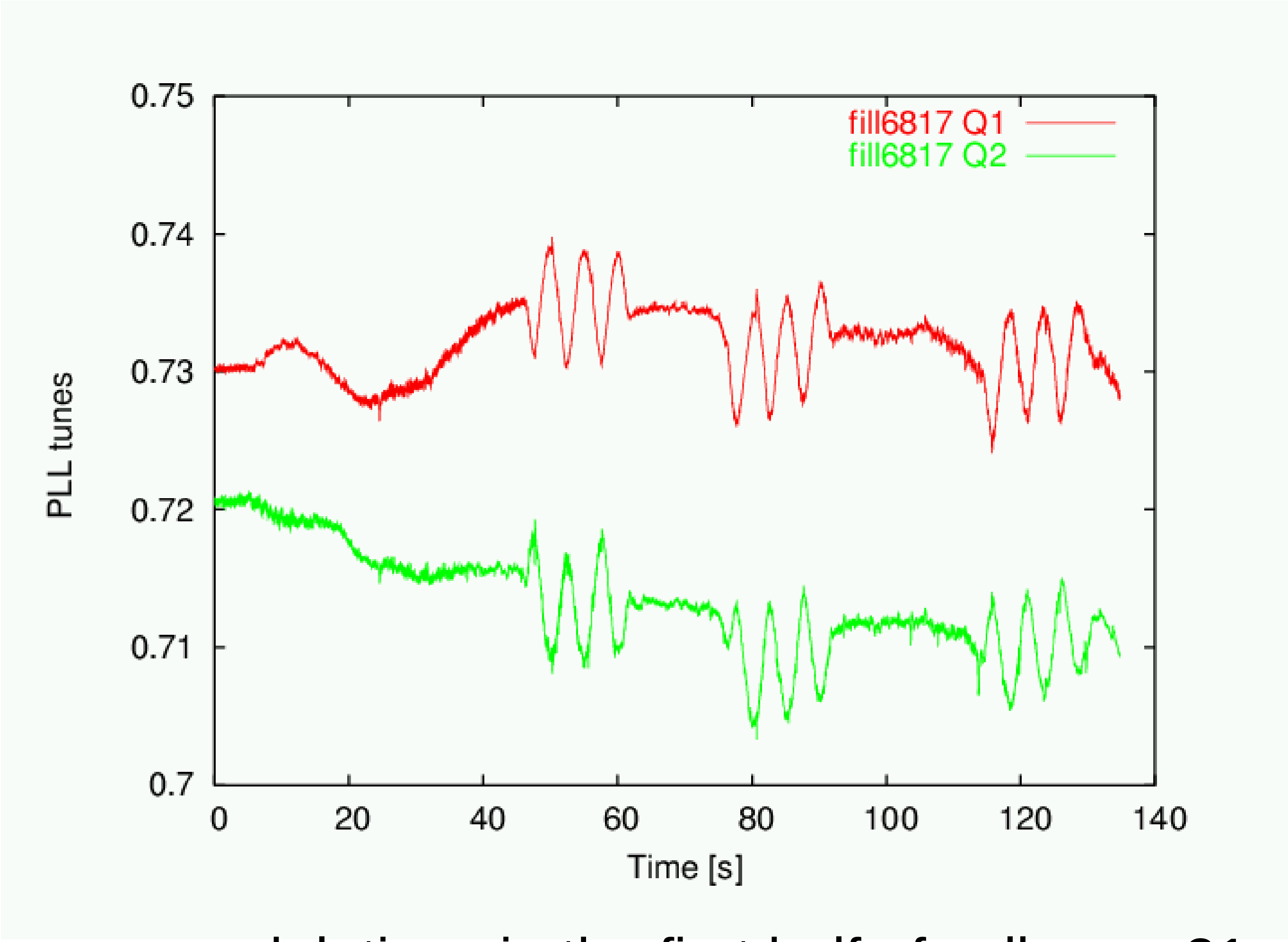
3. Tested at injection and store



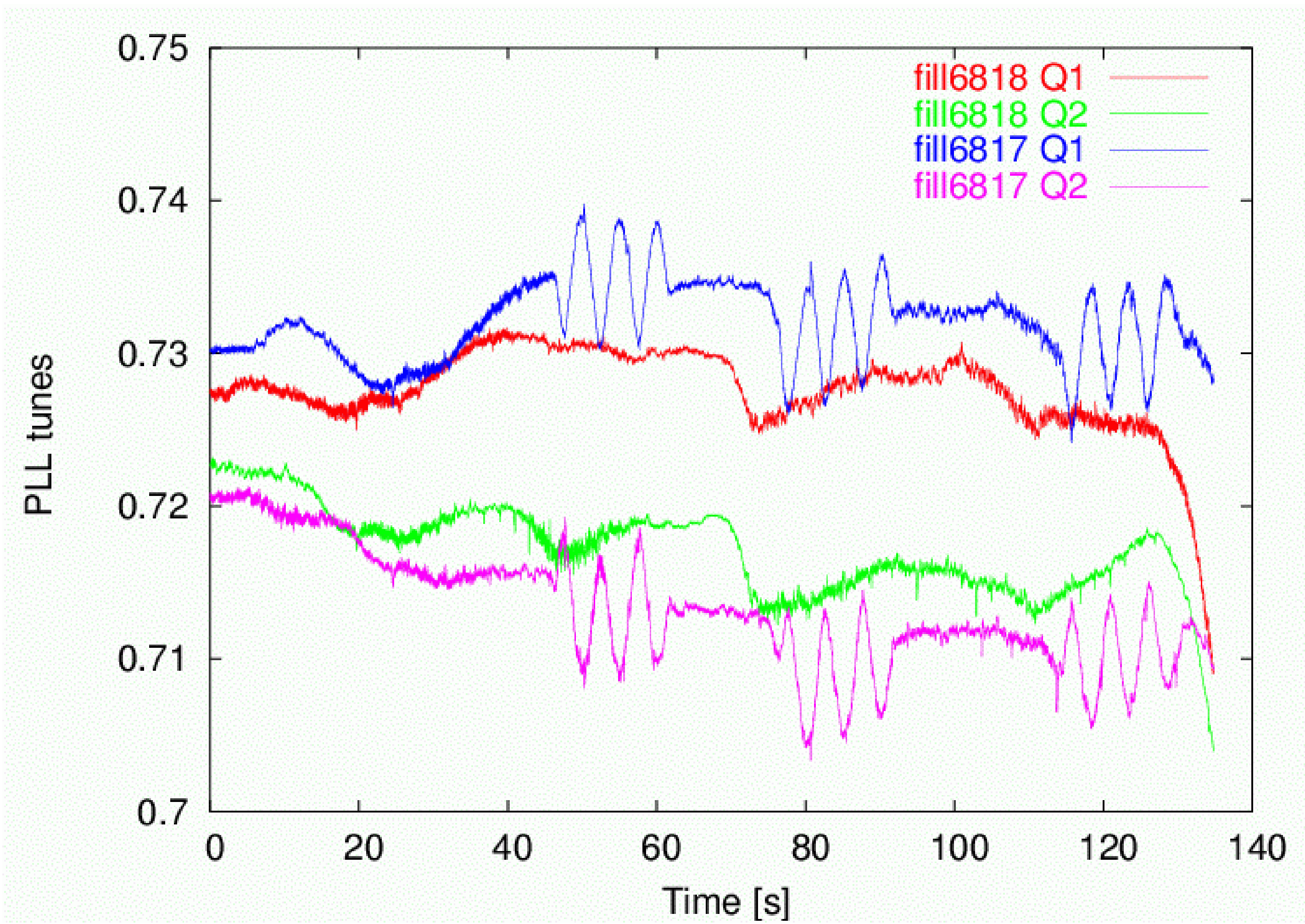


searching the correction strengths

4. Applied to ramp

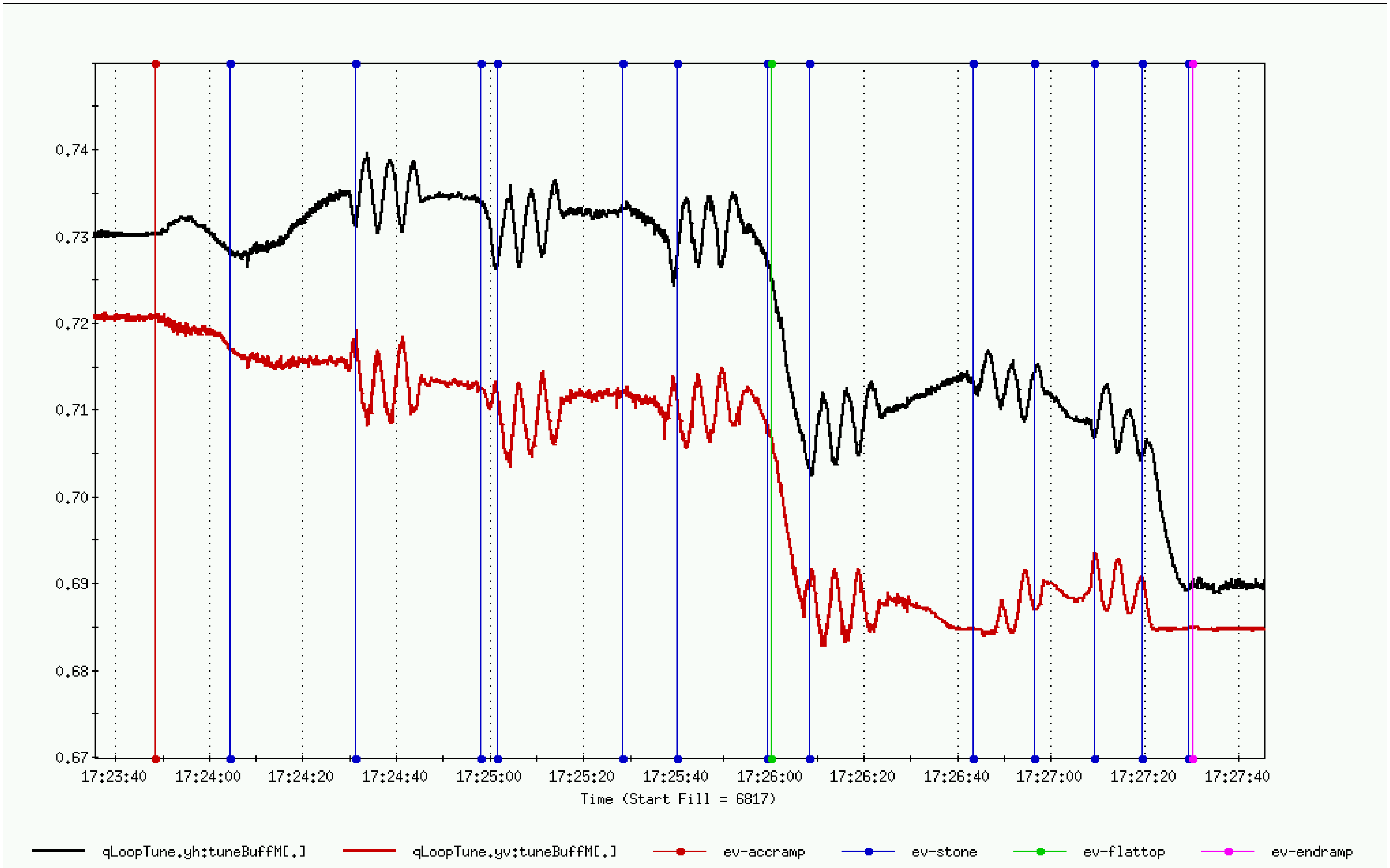


modulations in the first half of yellow pp21



Comparison before and after corrections.

No design tunes changes between the two ramps.



Seven-stone modulations in the whole yellow ramp, fill6817

5. Comments

- Coupling angle modulation is fast and robust.

  It has been applied to the RHIC ramp couping correction.

- Coupling angle modulation depends on the PLL tune measurements.

  PLL system suffers tune tracking under some coupling situation.
  Coupling feedback is one solution to the PLL tune losing track.

- Coupling angle modulation is hard to be used in feedback mode.

1) lacks the accurate k determination on ramp.
2) perturbs the beam with skew quadrupole modulation.

Feedback or feed-forward?

- Considering optics has more or less change from ramp to ramp, especially for LHC, and decoupling feedback will ensure the tune feedback, **therefore, feedback mode is preferred.**

- How to build the global decoupling feedback?

By now no succeessful demonstration.

1) What's the observables ?
   Only the tune split is not enough.
   No-perturbing observation is preferred.

2) What's the instrumentation?

BPM *or* PLL, *or other else?*

1. BPM ?

BPM data from the kicked beam, which causes the emittance blowup.
Beam dynamics of kicked beam is complicated, Coupling, nonlinear, decoherence all play roles.
Another important concern is the quality of BPM data.
Data anlysis is not staright-forwards, fitting is always needed, S/N ?

2. Phase Locked Loop (PLL)?

PLL has less perturbation to the beam
Coherent kicking
Outputs are straight-forward.

Therefore, PLL is preferred for the decoupling on ramp.

Six Coupling Observables

1. Definitions

In the view of instrumentation,

$$\left\{ \begin{array}{lll} x_n & = & A_{1,x} \cos[2\pi Q_1(n-1) + \phi_{1,x}] + A_{2,x} \cos[2\pi Q_2(n-1) + \phi_{2,x}] \\ y_n & = & A_{1,y} \cos[2\pi Q_1(n-1) + \phi_{1,y}] + A_{2,y} \cos[2\pi Q_2(n-1) + \phi_{2,y}] \end{array} \right. , \tag{10}$$

Besides the two eigentunes Q_1 and Q_2, we define another 2 amplitude ratios

$$\left\{ \begin{array}{lll} r_1 & = & |A_{1,y}|/|A_{1,x}| \\ r_2 & = & |A_{2,x}|/|A_{2,y}| \end{array} \right. . \tag{11}$$

and two phase difference

$$\left\{ \begin{array}{lll} \Delta\phi_1 & = & \phi_{1,y} - \phi_{1,x} \\ \Delta\phi_2 & = & \phi_{2,x} - \phi_{2,y} \end{array} \right. . \tag{12}$$

They are measurable from turn-by-turn digital BPMs and PLL pickups.

2. Simulations based one smooth-accelerator model

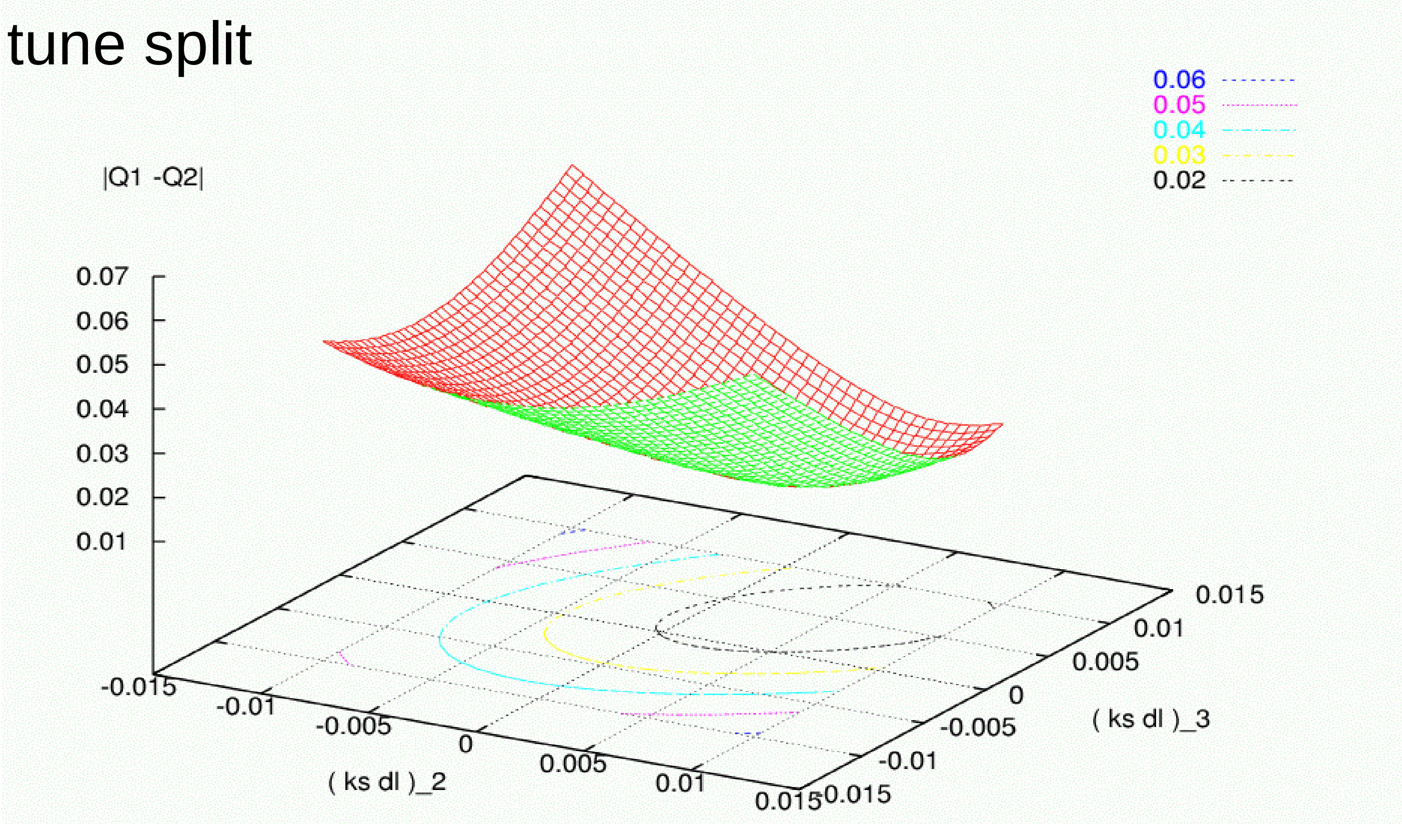


Figure 5: The tune split $|Q_1 - Q_2|$ in the 2-D decoupling scan.

amplitude ratio

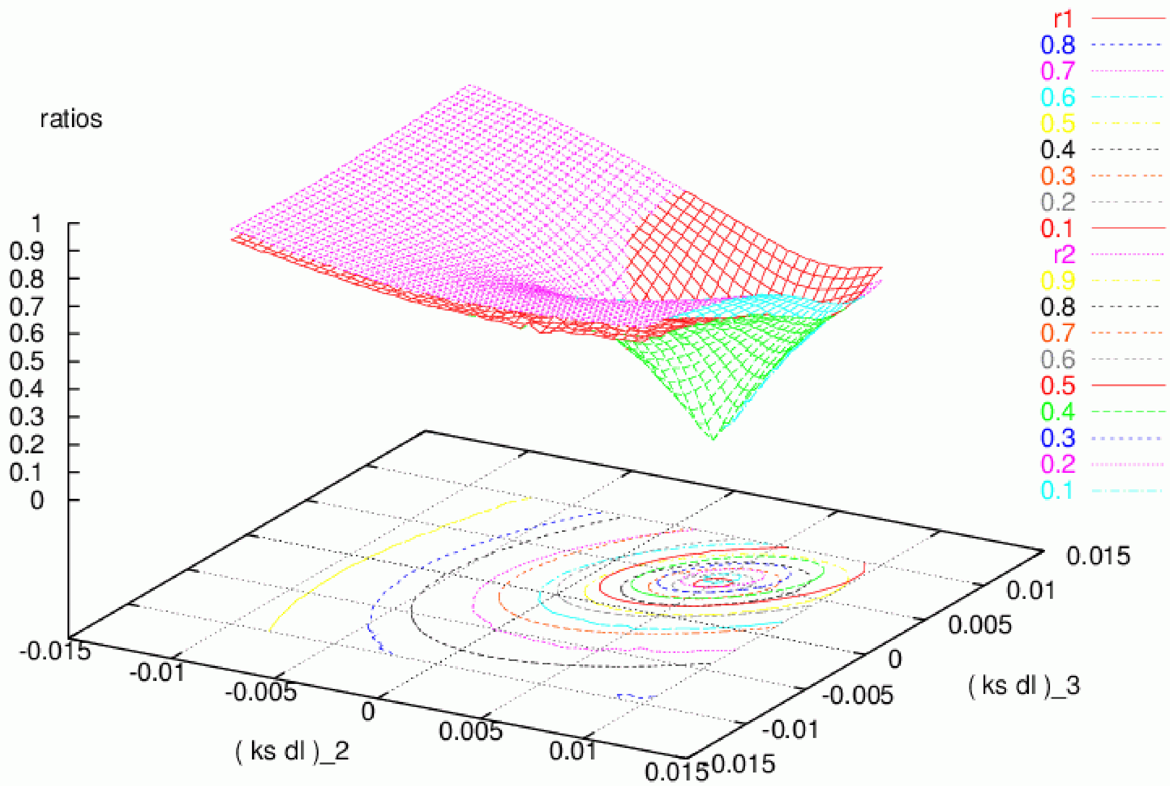


Figure 6: The amplitude ratios $r_{1,2}$ in the 2-D decoupling scan.

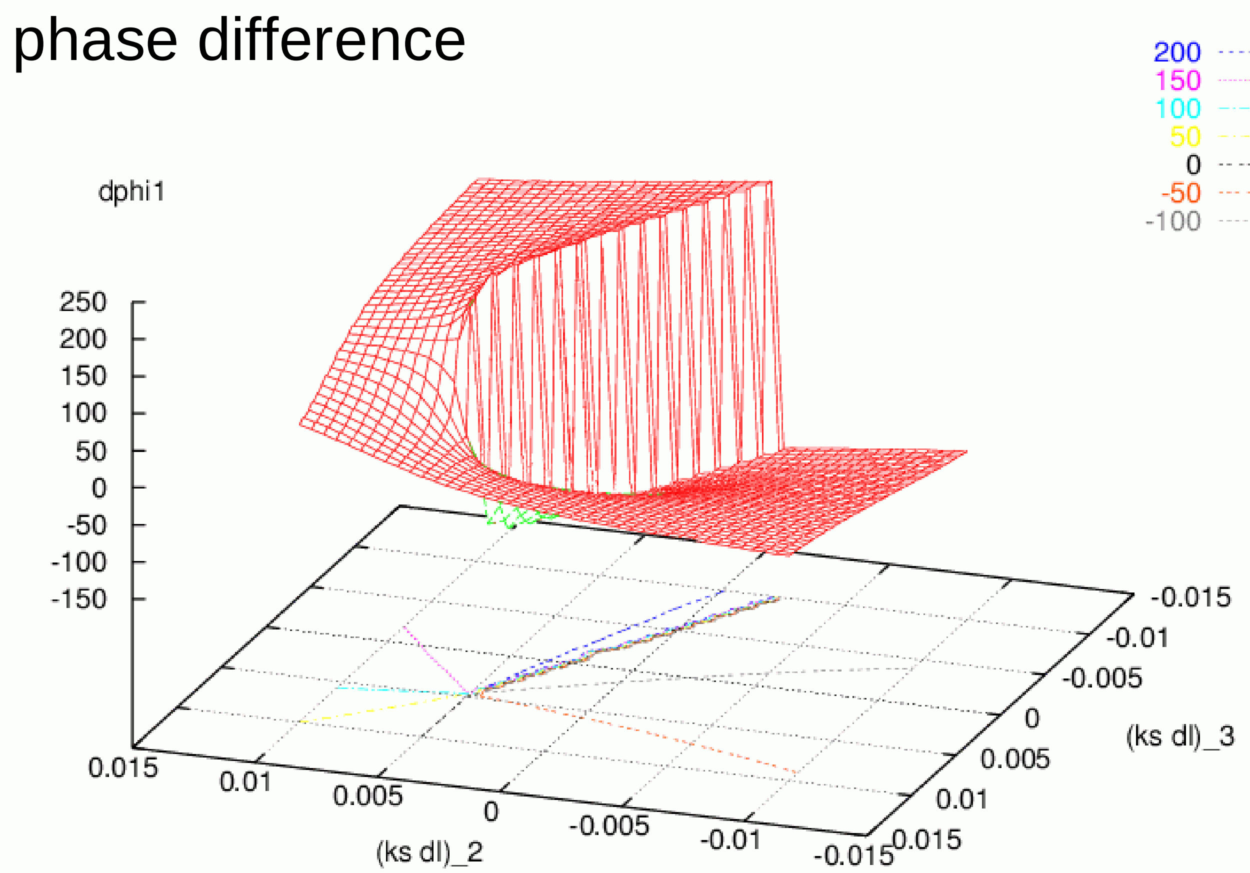


Figure 7: The phase differences $\Delta\phi_1$ in the 2-D decoupling scan.

Phase difference in 1-D scan

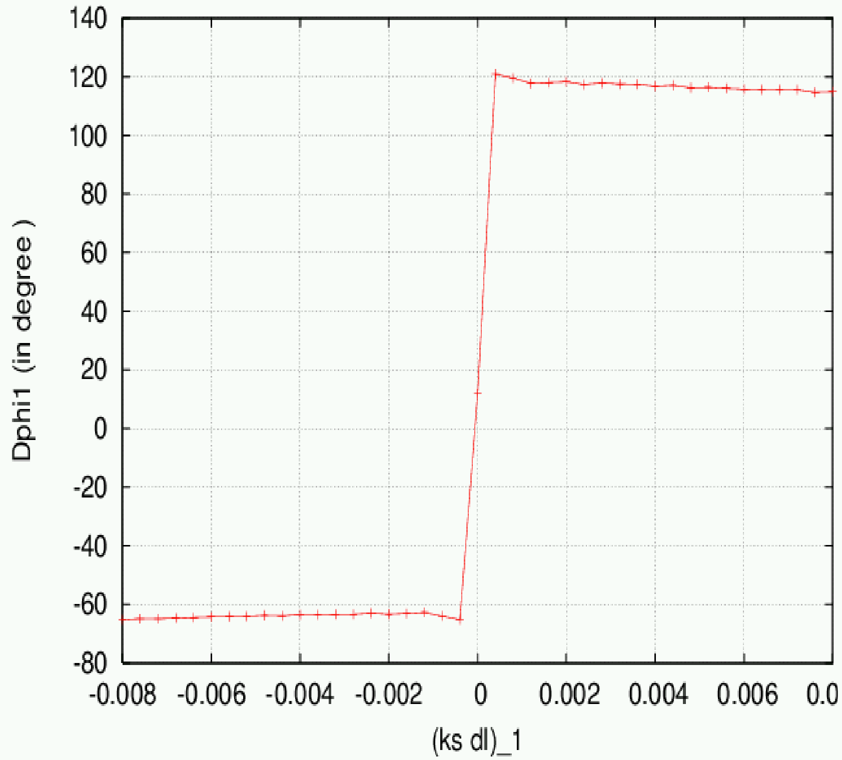


Figure 3: The phase differences $\Delta\phi_1$ in the 1-D decoupling scan.

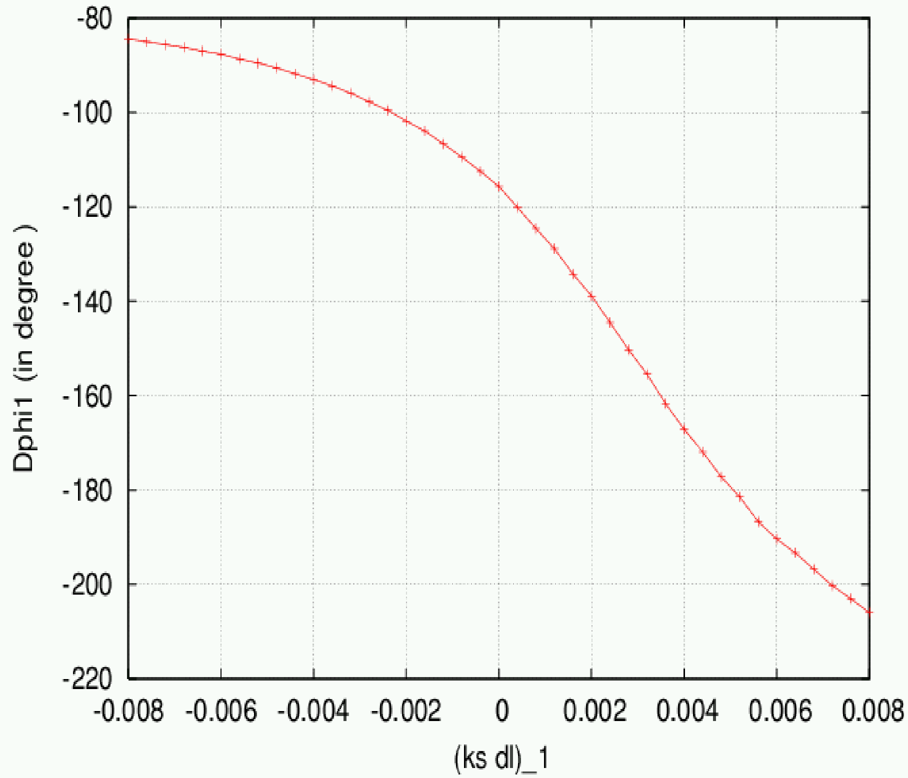


Figure 9: The phase differences $\Delta\phi_1$ in the wrong scan direction.

3. Analytical solutions

Based on coupling Hamiltonian perturbation theory

$$C^- = |C^-|e^{i\chi} = \frac{1}{2\pi}\int_0^L \sqrt{\beta_x\beta_y}k_s e^{i[\Psi_x-\Psi_y-2\pi\Delta\cdot s/L]}dl.$$

$$\left\{\begin{array}{lll} Q_1 & = & Q_{x,0} - \frac{1}{2}\Delta + \frac{1}{2}\sqrt{\Delta^2+|C^-|^2} \\ Q_2 & = & Q_{y,0} + \frac{1}{2}\Delta - \frac{1}{2}\sqrt{\Delta^2+|C^-|^2} \end{array}\right. .$$

$$\left\{\begin{array}{lll} R_I & = & \sqrt{\frac{\beta_y}{\beta_x}}\cdot\frac{|C^-|}{2\nu+\Delta} \\ R_{II} & = & \sqrt{\frac{\beta_x}{\beta_y}}\cdot\frac{|C^-|}{2\nu+\Delta} \end{array}\right. ,$$

$$\left\{\begin{array}{lll} \Delta\phi_{I,0} & = & \chi \\ \Delta\phi_{II,0} & = & \pi-\chi \end{array}\right. ,$$

$$|C^-| = \frac{2\sqrt{R_I R_{II}}\,|Q_I - Q_{II} - p|}{1+R_I R_{II}},$$

$$\Delta = \frac{(1-R_I R_{II})\,|Q_I - Q_{II} - p|}{1+R_I R_{II}}.$$

4. Possible phase loop for global decoupling

1) The 6 parameters can determine the coupling's amplitude and phase

Phase difference tells right decoupling direction.

The amplitude ratios tells the coupling amplitude.

In the right decoupling direction, tune split and amplitude ratio keep decreasing.

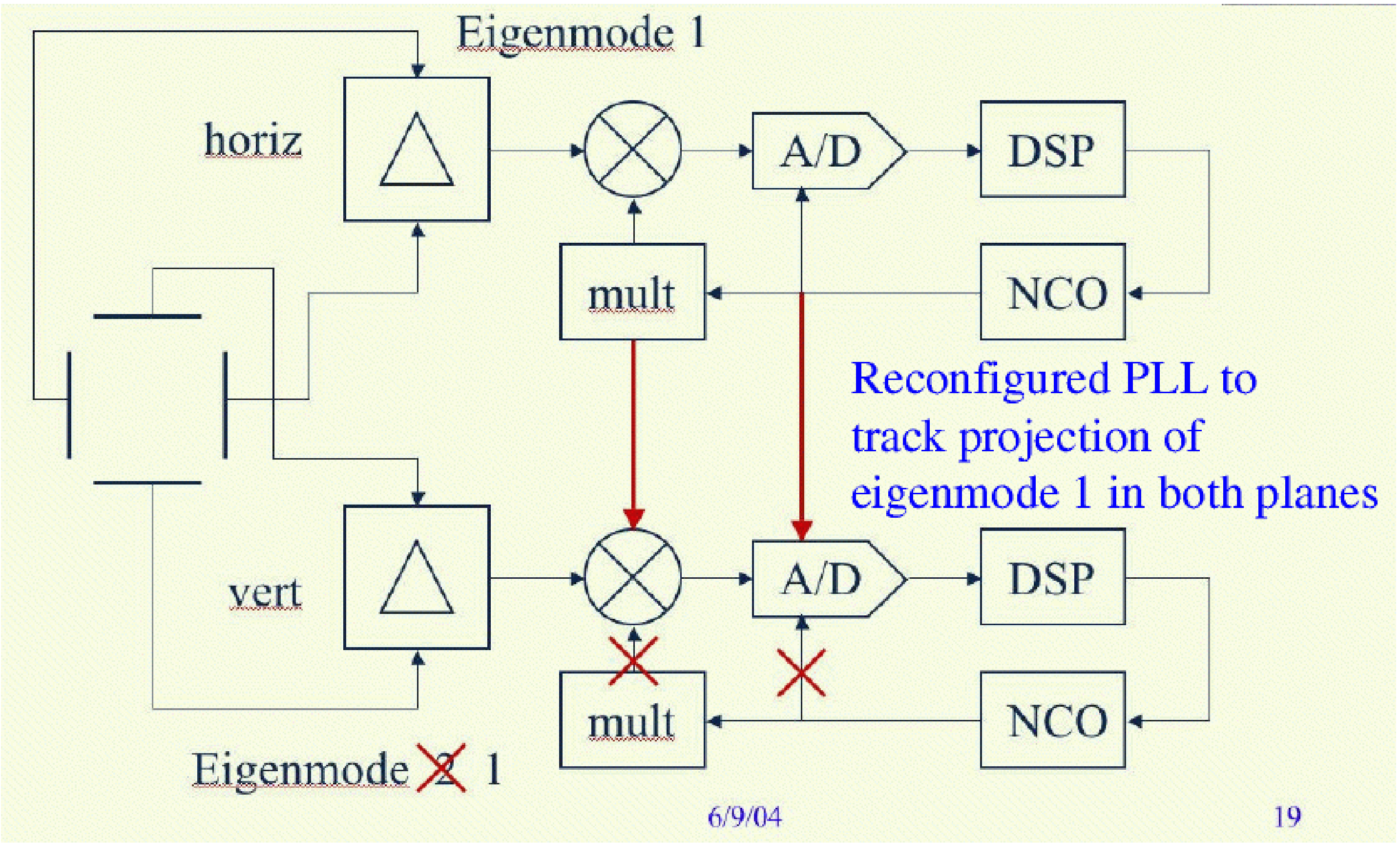
2) The decoupling direction, or coupling coefficient's angle, is given by a certain combination of the skew quadrupole strengths.

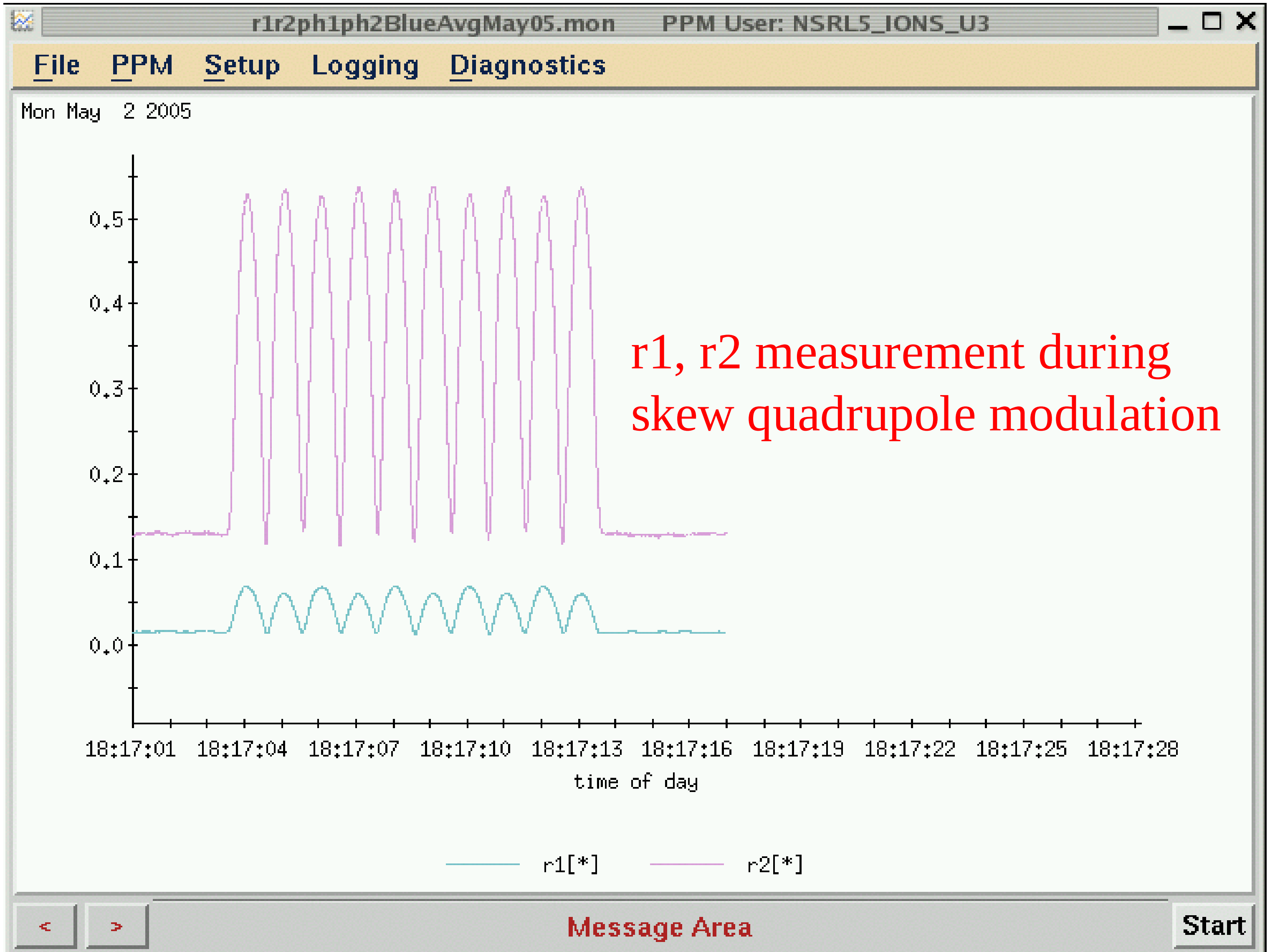
$$C^- = |C^-|e^{i\chi} = \frac{1}{2\pi}\int_0^L \sqrt{\beta_x\beta_y}k_s e^{i[\Psi_x-\Psi_y-2\pi\Delta\cdot s/L]}dl.$$

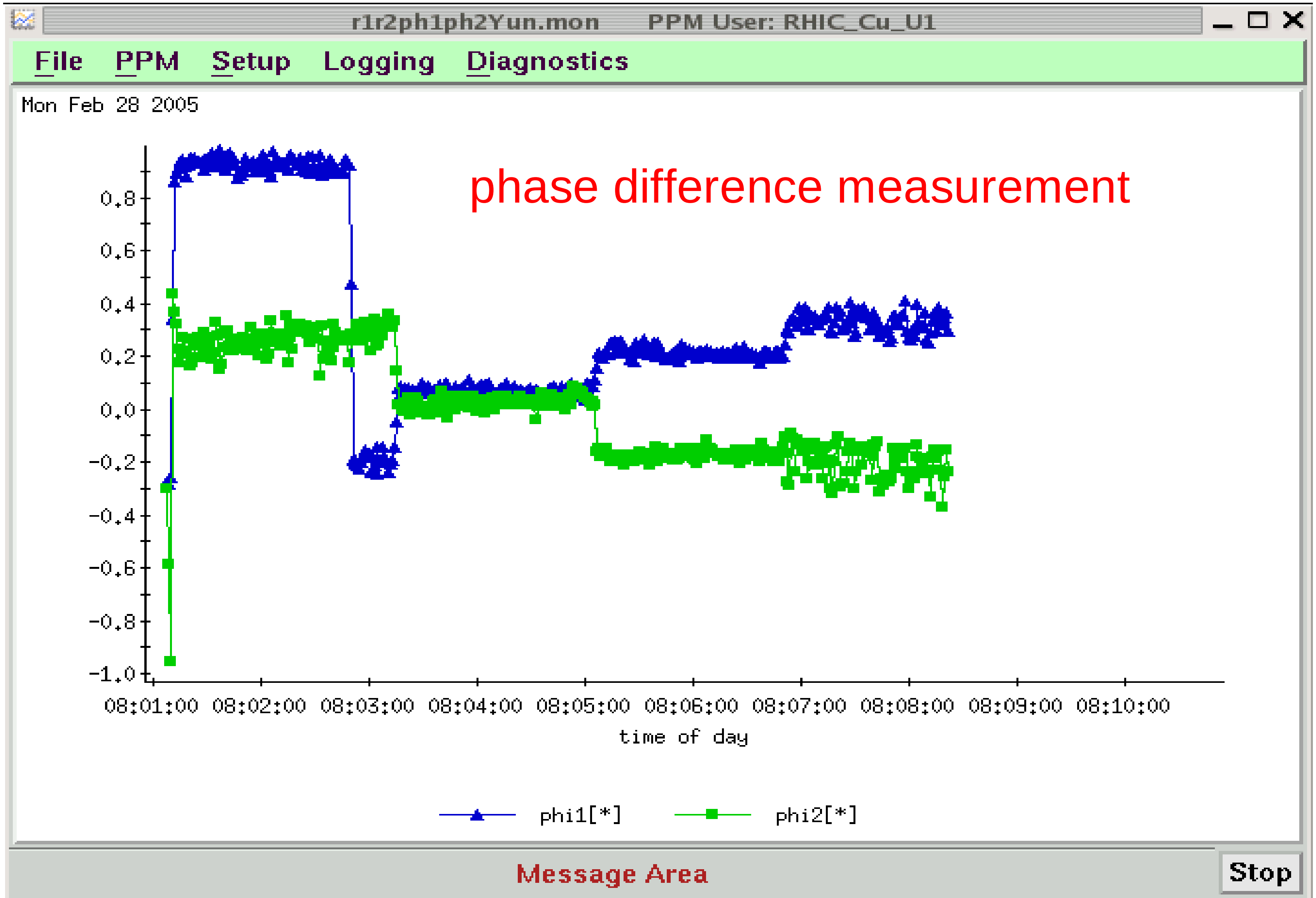
Knowing the phase difference, the right combination of the skew quadrupole strengths can be calculated from optics model, or calibration from coupling angle modulation.

5. Measurement of the 6 parameters

The measurement is the key to the decoupling feedback.
The PLL system is reconfigured for this measurement.




r1r2ph1ph2BlueAvgMay05.mon PPM User: NSRL5_IONS_U3
File PPM Setup Logging Diagnostics
Mon May 2 2005
0.5
0.4
0.3
0.2
0.1
0.0
18:17:01 18:17:04 18:17:07 18:17:10 18:17:13 18:17:16 18:17:19 18:17:22 18:17:25 18:17:28
time of day
r1[*]
r2[*]
r1, r2 measurement during skew quadrupole modulation
Message Area
Start


r1r2ph1ph2Yun.mon PPM User: RHIC_Cu_U1
File PPM Setup Logging Diagnostics
Mon Feb 28 2005
phase difference measurement
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
08:01:00 08:02:00 08:03:00 08:04:00 08:05:00 08:06:00 08:07:00 08:08:00 08:09:00 08:10:00
time of day
phi1[*]
phi2[*]
Message Area
Stop

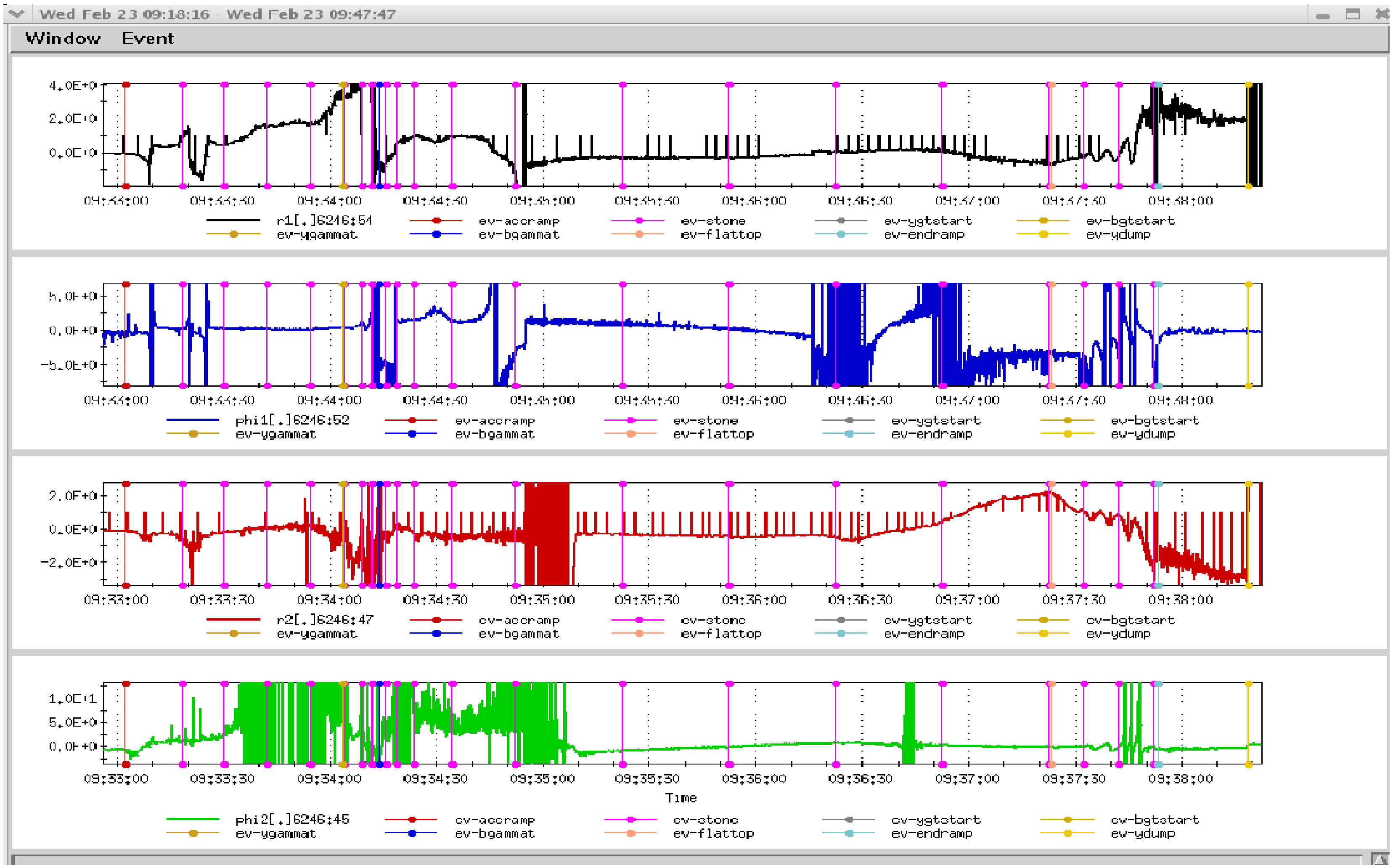
One measurement on the ramp

r1

dphi1

r2

dphi2



Summary

1. N-turn map correction method need further verifying.

2. Coupling angle modulation is more fast and robust.
   It has been applied to RHIC ramp coupling correction in feed-forward mode.

3. Six coupling observables are hopeful for the future non-perturbative global decoupling feedback.

4. The key point for PLL based global decoupling feedback is to be able to measure the amplitude ratio and phase differences with PLL sysytem. Beam experiment is under way.